AËROGRAPHY, THE SCIENCE OF THE STRUCTURE OF THE ATMOSPHERE

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Except in its relation to aëronautics, few people appreciate the significance of upper-air exploration. It is much more than the getting of high-level temperatures, interesting as these may be. It is the prospect of a wider knowledge of the aërial ocean which lures the meteorologist. Until this work be accomplished, a man looking up at the clouds and with a map giving only surface conditions, can know no more about the sea of air above him than primitive man knew of the sea of water when he first ventured upon it. Small wonder that meteorology has made such slow progress in forty years; no wonder that weather maps seemingly alike should be followed by different conditions.

The term *aërography* is new, making its initial appearance perhaps with this article. Its meaning remains to be given; and at present we can hardly hope to do this so fully and completely that later modification will not be necessary. Like its analogues *geography* and *hydrography,* aërography, taken literally, means a description of the air. In the past four or five years the term *aërology* has been used in connection with the exploration of the upper or so-called free air; but it would seem more appropriate to let this term embrace the whole domain of atmospherics, while the word aërography might well be restricted to a description of the atmosphere at various levels. The flow and counter-flow of the air, the pressures, temperatures, humidities, dust content, electrical charge, etc., would thus be proper subjects for consideration under aërography, as well as their functions and relation to life; but such broader questions as the evolution of the atmosphere, its relation to the planet and to planetary phenomena, would be appropriately discussed under aërology.

Through the initiative of two non-official aërographers, the late Teisserenc de Bort and the late A. Lawrence Rotch, it has recently been established that the atmosphere is not of a homogeneous and uniform character but consists of two great divisions, a lower region, where temperature falls with elevation, and an upper region (in general higher than nine kilometers), where the temperature increases with elevation. The latter has been called the isothermal region, but such a name is rather misleading and should be discontinued in favor of Teisserenc de Bort's term *stratosphere.* The lower portion may appropriately be called the *troposphere.*

Pioneer but none the less excellent aërographies are "Charts of the Atmosphere for Aëronauts and Aviators," by A. Lawrence Rotch and

Andrew H. Palmer, published in 1911,[1] and the "Structure of the Atmosphere in Clear Weather," by C. J. P. Cave, 1912.[2] The introduction to the first-named volume is so brief and tells its story in such a straightforward way that we may well quote it entirely. Professor Rotch says—

"Although the exploration of the air, which was begun twenty years ago in France and Germany and at Blue Hill, was undertaken for the elucidation of meteorological problems, yet much of the data obtained is of importance for the new art of aërial navigation. Accordingly, some of the information which has been gathered by the Blue Hill Observatory in the United States and on the Atlantic Ocean through co-operation with a similar French institution, is here presented in a practical form for aëronauts and aviators. The term aëronaut is used to designate the pilot of a balloon, while aviator is restricted to the pilot of a flying-machine heavier than air.

"Thus the work which Lieutenant Maury did fifty years ago for the surface winds and ocean currents is now extended into the overlying ocean of air. This is the more necessary, since the whole aërial ocean is subject to stronger commotions than even the surface of the aqueous ocean and is navigable throughout a depth equal to that of the latter.

"The following charts, which are believed to be the first of the kind adapted to the use of airmen, relate only to portions of the United States and the Atlantic Ocean, but they will doubtless be perfected by aërologists and extended in the near future to other parts of the globe."

Cave's book is essentially an investigation of the wind currents in the light of the results obtained by sounding-balloon work in Great Britain. Certain structural types are recognized and considered in their relation to the surface wind, the gradient wind, and the general pressure and temperature distribution. The strongest air motion or wind is found just below the stratosphere; and it would seem that pressure changes originate in this region and probably control conditions throughout the lower atmosphere. We may note here the somewhat startling suggestion of Dr. W. N. Shaw[3] that wind variations may better be referred to this upper level than to the surface. Cave is of the opinion that such a base simplifies the problem. For example, working downward, he finds[4] that in a certain ascent (Sept. 15, 1911) the west-east component of air flow decreased from +32 m/s. (meters per second) at a height of 9 kilometers to —8 m/s. at 1 kilometer. This means that the *flow was reversed with approach to the earth's surface.* Similarly the north-south component decreased from +12 m/s. to —10 m/s.

Aërographers, then, may well begin their work with these two volumes by Rotch and Cave. If the titles sound somewhat strange to our ears let us recall the quaint expression used by the Dorset squire, Robert Boyle,

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[1] 24 full-page charts, with descriptions. John Wiley & Sons, New York, 1911. (Review in *Bull. Amer. Geogr. Soc.*, Vol. 44, 1912, pp. 861-862).

[2] xii and 144 pp. University Press, Cambridge, 1912. (Review in *Bull. Amer. Geogr. Soc.*, Vol. 45, 1913, p. 62.)

[3] *Quart. Journ. Royal Meteorol. Soc.*, Vol. 38, 1912, pp. 46-48, and *Nature*, Vol. 88, 1911-12, p. 141.

[4] *Op. cit.*, p. x.

in his book published in 1660, entitled "The Spring of Air." This volume undoubtedly marks the beginning of positive knowledge regarding the physical processes of the atmosphere, for, crucial as were the experiments of Torricelli, Pascal, and von Guericke, it was Boyle who showed us that the air was elastic; and his law of pressure and volume relation, expanded later into the characteristic equation of a pure gas, lies at the bottom of our modern thermodynamics.

We shall appropriate the term "structure" from Cave, for aërography must be, in essence, a description of the structure, or make-up, of the atmosphere. But every structure must rest upon a base; and in aërography it may be necessary to discard the old sea-level plane so familiar to us, but now known to be of somewhat doubtful value, when atmospheric conditions over continental areas are to be reduced downward. How can we get another base plane? It may be remarked at this point that it is a difficult matter to adequately represent atmospheric conditions on a flat map. The daily weather map in its present form—and there has been practically no change in forty years—by no means represents conditions at the bottom of the ocean of air; and perhaps much of the uncertainty of forecasting may be traced to faulty graphics. Again, the aërographer must be able to show on the base not only pressure and temperature gradients, but water-vapor content and, for lack of a better name, dust load, meaning thereby small and large nuclei of condensation, ions, and electrons. And it will be a great step forward when these can be shown for all levels. Then, as a geographer would chart continents, coasts, and islands, the aërographer would chart hyperbars and infrabars—regions of excessive air flow and regions of no flow or stagnation—also levels where the interchange of air was mainly by "advection," or horizontal motion, and where the interchange was by "convection," or vertical motion, using terms introduced by Ernest Gold in his prize essay on "The International Kite and Balloon Ascents."[5]

With such a base map and such auxiliary charts the winds and clouds will take on a new significance and can be studied to advantage. The layman as well as the expert would be able to follow the general circulation, and follow intelligently the average west-to-east drift around one pole and the reversal at the other. Interruptions and displacements of the great air streams could be correlated with abnormal weather conditions and give us firmer ground in forecasting. At present one must applaud rather the valor of the forecaster than the value of the forecast. Such charts would go far in settling discussions regarding the origin of cyclones and anticyclones, discussions which, so long as they are based upon present charts of air flow, must continue to be unsatisfying.

Returning again to the apparent structure of the atmosphere: As indicated by the models used by Cave, it would seem to be entirely feasible to

[5] *Geophysical Memoirs No. 5* (= pp. 61-144) Meteorological Office, London, 1913. Reference on p. 109.

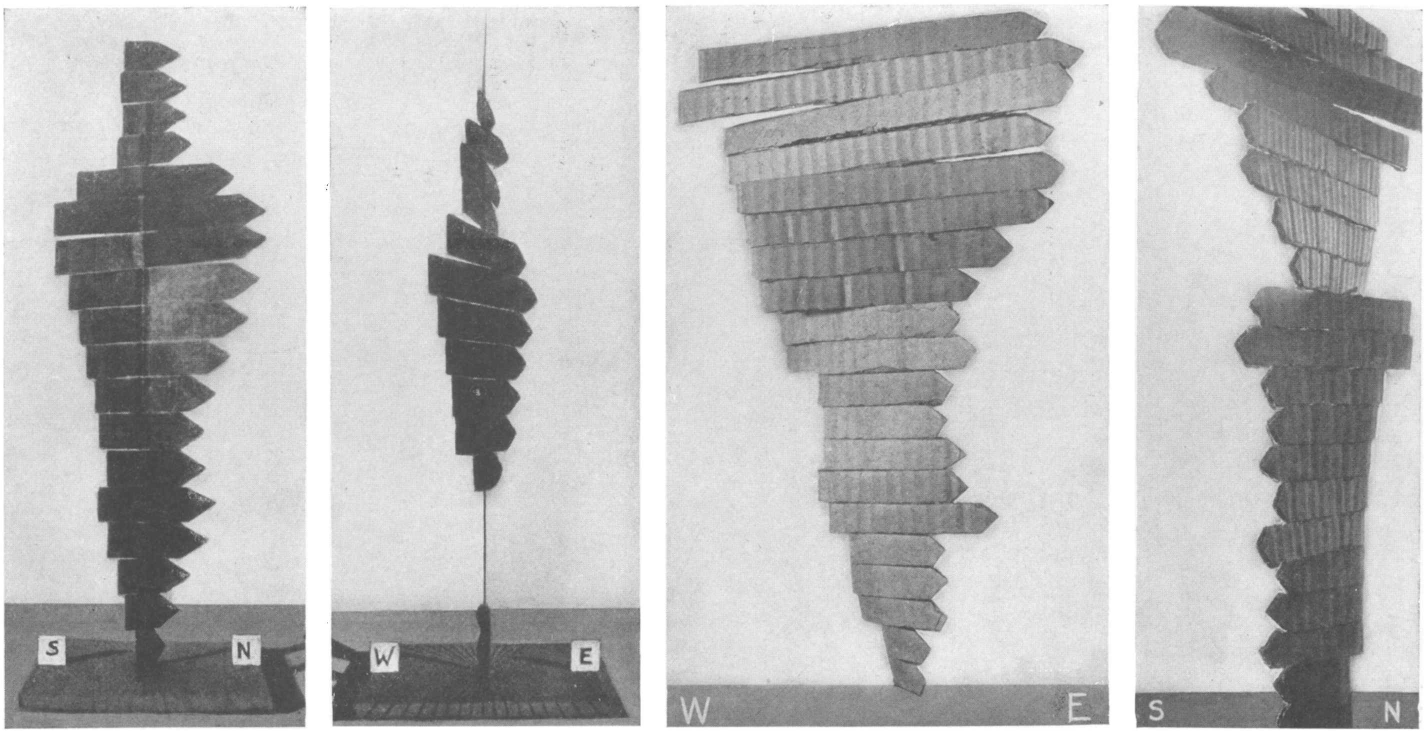
show the sequence of wind velocities and directions at various levels appropriate to certain types of weather and certain seasonal conditions. Let us also consider Shaw's suggestion of the stratosphere as the principal plane of reference. It may seem strange to attempt to use so variable a level as the base of the stratosphere, yet it may be after all most appropriate, since the atmosphere is itself variable and mobile. The geographer deals with a solid earth, and there is no flow horizontally or vertically. True, we live upon a rotating geoid; but our sensations and impressions are such as would be common to dwellers upon a flat surface. We are handicapped in comprehending air motion because all our experiences are based upon impressions of level and fixed planes. We are, for example, absolutely unconscious of any deflective effect of a moving air current due to the earth's rotation.

It is a peculiar fact about the stratosphere and one full of significance that it does not remain at a fixed height but varies with season and latitude. At the equator, as we rise in air, the temperature continues to fall to a much greater height than in temperate latitudes. Indeed the lowest temperature, probably the lowest natural temperature, is found above the equator. This state of affairs was anticipated by Teisserenc de Bort and Rotch and has now been proven by certain ascensions. Thus at Batavia, Java, on December 4, 1913, the sounding balloon reached a height of 26 kilometers, entering the stratosphere at 17 kilometers and recording a temperature of 192° A (—112°F). In other words, the stratosphere is highest over the equator and lowest over the poles, so far as we know.

Expression of air flow, then, is the first desideratum in aërography. The aërographer, however, is at present in something of the quandary in which a geographer would be who depended upon a scale of distance that could be applied only in one direction. A map based on such coordinates is, of course, of limited value, and this is true in aërography if we measure only horizontal and not inclined and vertical flow.

Investigators have been singularly slow in measuring and expressing air flow. Records of horizontal flow date back to the middle of the seventeenth century, or rather began about that time in Italy; but the measurement of vertical flow is still wanting, although W. H. Dines emphasized the need in 1887 and gave us a new form of anemometer. The whole series of wind measurements made in various official weather services throws little light on the vertical movement of the air. And what is still more disheartening, there is a very large error in the horizontal velocities as published.

It is of the utmost importance that we know something or have some way of representing the vertical component of motion of the air. The formation of rain, local and general air drainage, pressure gradients, and temperature gradients are affected by the duration and strength of ascensional and descensional currents. In aëronautics, too, this matter is important.



FIGS. 1 to 4—Models representing vertical wind distribution.

Figures 1 and 2 represent the conditions at Ditcham, Hampshire, England, on October 1, 1908; Figures 3 and 4, the conditions at Blue Hill Observatory, Mass., on August 12, 1910. Each model is shown from two sides (Figures 1 and 4 from the east, and Figures 2 and 3 from the south) so that the orientation of the arrows may be seen. The arrows fly with the wind; the length indicates the velocity at that level. In Figures 1 and 2 each arrow represents an air stratum of 1,000 meters and in Figures 3 and 4 of 500 meters.

Figures 1 and 2 are taken from Cave's "The Structure of the Atmosphere in Clear Weather," 1912. Figures 3 and 4 are from models based on soundings made at Blue Hill Observatory.

In a recent paper[6] we find the conclusion that on cloudless days the average upward velocity at the given point was about 0.5 meter per second, while on days with detached cumulus clouds the average velocity was about 2 meters per second.

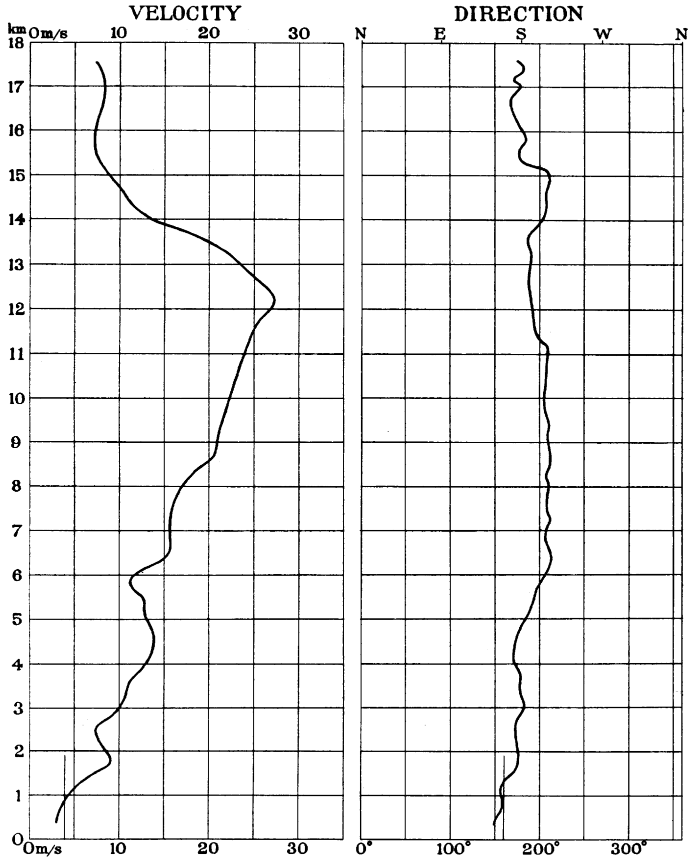


Fig. 5—Diagram showing, for the wind conditions at Ditcham, England, on October 1, 1908, represented by the model of Figures 1 and 2, the relation of velocity and direction to height. Based on a figure in Cave's "The Structure of the Atmosphere in Clear Weather," 1912.

The sounding balloon was watched until it burst, and the highest point deduced from the meteorograph trace was used as the highest point for wind observations; up to 4 kilometers the wind observations were deduced from the two-theodolite method; above this the balloon was supposed to have a uniform acceleration up to the highest point reached, and the wind velocities were calculated on the one-theodolite method.

But the running of the air—to translate literally the old Greek definition of wind—is not a steady, uniform, and continuous motion. On the contrary the flow is frequently of an intermittent character. There are lulls and gusts; and there are eddies and vortices, small and large. This uneven-

[6] Report on Wind Structure No. 4 (for 1912-13): Papers by J. S. Dines. Meteorological Office, London, 1914.

ness of flow was brought out clearly by Professor S. P. Langley in his paper on "The Internal Work of the Wind."[7] In the light of present achievements in aviation it is interesting to read his statement, which seemed so fantastic when written, that an indefinite source of power for the maintenance of mechanical flight might lie in this unevenness of flow, which he called the internal work of the wind. And he adds, what is of some importance in aërography, that "the actual effect of the free wind, which is filled with almost infinitely numerous and incessant changes of velocity and direction, must differ widely from that of a uniform wind such as mathematicians and physicists have almost invariably contemplated in their discussions."[8]

In order to illustrate with more detail the structure of the free air as determined by modern soundings, we have borrowed from Cave's book one of the many models shown (Figs. 1 and 2). This represents the wind distribution on October 1, 1908, seen from the east and from the south. The greatest height in this case was 17.6 kilometers. The diagram (Fig. 5) shows the relation of wind elements to heights.

The structure indicated by Figures 3 and 4 is that of a typical midsummer fair-weather day on the New England coast. There was no sea breeze nor even the northeast inflow found frequently under anti-cyclonic conditions. The structure is exceedingly uniform. In the lower strata the velocities average from 2 to 6 meters per second, and the flow is fairly steady in direction horizontally. There is a tendency to shift to the north up to about 2,800 kilometers, then an increasing westerly component. The sky was practically without clouds. An extensive high area moving east at a normal rate overlay the eastern half of the United States. In the Ohio Valley and Lake Region the pressure ranged from 1,020 to 1,025 kilobars. The twenty-four hours following were without rain in Ohio, Pennsylvania, New York, and New England. In fact the day was a typical fair day, and the structure may be said to indicate a certain stability and absence of turbulence.

In general the sub-stratosphere is the region of maximum air motion. Again, the modification of wind direction seems to progress downward. Perhaps I can not do better than sum up the impression which such models of structure give than by quoting the words of Dr. W. N. Shaw:[9]

"It appears that we must regard the sub-stratosphere and the regions above as the dynamical laboratory of the atmosphere, where the main causes of pressure changes originate, and the troposphere beneath the sub-stratosphere as the physical laboratory of the atmosphere, where cloud, rainfall, and other physical phenomena are produced by local causes,

[7] *Smithsonian Contributions to Knowledge*, Vol. 27, No. 2, Washington, 1893. 23 pp.

[8] Langley Memoir on Mechanical Flight, *Smithsonian Contributions to Knowledge*, Vol. 27, No. 3, Washington, 1911. 320 pp. Reference on p. 42.

[9] The Free Atmosphere in the Region of the British Isles: Second Report. By W. H. Dines, with a preface by W. N. Shaw. *Geophysical Memoirs No. 2* (= pp. 11-50), Meteorological Office, London, 1912. Reference on p. 22.

induced, in some cases, by the effect of the dynamical changes in the upper regions."

Thus far we have laid stress on the flow of the air. But temperature and other data are also available. Thus W. H. Dines[10] has given us the normal isopleths of temperature and also pressure from sea level to a height of 20 kilometers and curves showing the local difference from the mean temperature for each level. The Geophysical Institute of Leipzig, under the direction of V. Bjerknes, is publishing a series of synoptic charts for three-day periods of the year 1910 showing the conditions at different levels.[11]. The atmosphere is divided into ten principal isobaric levels. In the last number issued, representing the period August 8, 9, and 10, 1910, the stations furnishing soundings were Trappes near Paris, Uccle near Brussels, Pyrton Hill near London, Crinan near Glasgow, Oughterard on the west coast of Ireland, Manchester, Pavia, Friedrichshafen on Lake Constance, Strassburg, Hamburg, Lindenberg near Berlin, Vienna, Pavlovsk near Petrograd, Nijni-Oltchedaeff in southwestern Russia, and Munich. There were also auxiliary cloud observing and mountain stations. With the data for these stations we can at once construct over Europe the heights in dynamic meters for each stratum of 100 kilobars and also what may be called the relative topography, i. e. the value in dynamic meters between each successive level, or, in other words, the gradient for the aërographic topographer.

Thus the making of aërographic surveys is already under way. Perhaps the day is not so far distant when charts of air structure will be available for consecutive tri-hourly periods for the use of aviators and aërial engineers, for the time is rapidly approaching when problems of transportation via air routes must be considered.

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[10] *Op. cit.* sub 9, p. 29.

[11] Synoptische Darstellungen atmosphärischer Zustände: Jahrgang 1910. *Veröffentl. des Geophys. Inst. der Univ. Leipzig:* Heft 1, Zustand der Atmosphäre über Europa am 6. Januar 1910 (Leipzig, 1913); Heft 2, —— am 2., 3. und 4. Februar 1910 (Leipzig, 1913); Heft 3, —— am 18., 19. und 20. Mai 1910 (Leipzig, 1914); Heft 4, —— am 8., 9. und 10. August 1910 (Leipzig, 1915).